Evidence for a population of beamed radio intermediate quasars

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ABSTRACT

Whether radio intermediate quasars possess relativistic jets as radio-loud quasars is an important issue in the understanding of the origin of radio emission in quasars. In this letter, using the two-epoch radio data obtained during Faint Image of Radio Sky at Twenty centimeter sky (FIRST) and NRAO VLA Sky Survey (NVSS), we identified 89 radio variable sources in the Sloan Digital Sky Survey. Among them, more than half are radio intermediate quasars ($RL = f_{20cm}/f_{2500\AA} < 250$). For all objects with available multiple band radio observations, the radio spectra are either flat or inverted. The brightness temperature inferred from the variability is larger than the synchrotron-self Compton limit for a stationary source in 87 objects, indicating of relativistic beaming. Considering the sample selection and the viewing angle effect, we conclude that relativistic jets probably exist in a substantial fraction of radio intermediate quasars.

Subject headings: Galaxies: jets – quasars: general – radio continuum: galaxies

1. Introduction

The radio relative to their bolometric luminosity in quasars is one of the greatest variance in the quasar's Spectral Energy Distribution (SED, Elvis et al. 1994). The distribution of the radio loudness, the ratio of radio flux to the optical one, appears bimodal with about 90% being radio quiet and 10% radio loud (Kellermann et al. 1989; Falcke et al. 1996a; Ivezić et al. 2002, 2004; c.f., Hooper et al. 1995; White et al. 2000; Cirasuodo et al. 2003).

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The confirmation and the origin of this radio dichotomy is one of the major issues in AGN study. Several scenarios were proposed to explain the large range of radio strengths. The basic assumptions fall into two main categories: (1) The central engines in the two types are assumed fundamentally different. For example, the formation of radio jets is associated with the spin of black hole (Blandford 1990 and reference therein) or with very low mass accretion rate onto the supermassive black hole (SMBH; Boroson 2002). (2) The weak of radio emission in the radio quiet is attributed to the rapid deceleration of relativistic jets on parsec scales, such as caused by the strong interaction with either gas in the inner nucleus (e.g., Falcke et al. 1996b) or the strong radiation produced by the quasars (Ghissellini et al. 2004).

The close related question is whether radio jets in radio quiet quasars are relativistic as in radio loud objects. However, the measurement of proper motion is very difficult in general due to their weak radio emission and in particular due to the small size of the radio source. Even at the VLBI resolution, the radio sources in most low redshift radio quiet and radio intermediate quasars remain un-resolved or at best are marginally resolved (Falcke et al. 1996b; Blundell & Beasley 1998; Ulvestad et al. 2005). The brightness temperatures or their lower limits are in the range of 10^{8-11} K, consistent with being the nucleus origin. Superluminal motion at sub-parsec scale has been detected in two radio intermediate quasars III Zw 2 (Brunthaler et al. 2002, 2005) and PG 1407+263 (Blundell, Beasley & Bicknell 2003), suggesting that the radio jets in those sources be relativistic. Radio intermediate quasars ($RL < 250$ for flat spectrum radio sources, Falcke et al. 1996a) were proposed to be the boosted radio quiet quasars based on the statistical properties of the [OIII] luminosity, their flat radio spectra, the high brightness temperature and the large amplitude variability (Miller et al. 1993; Falcke et al. 1996b; c.f., Barvainis et al. 2005).

As for the radio loud quasars, variability is a useful method to address whether a relativistic jet is present. The brightness temperature derived from variability is usually larger than that derived from the VLBI imaging in radio loud quasars (Valtaoja et al. 2003). In this paper, we present a detailed study of radio variability of the SDSS quasars by using the two epoch radio data derived from the Faint Image of Radio Sky at Twenty centimeters (FIRST, Becker et al. 1995) and NRAO VLA Sky Survey (NVSS, Condon et al. 1997). Throughout this paper, we assume $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$.

2. The Sample and Radio Variability

The sample was selected by cross-correlating the third Data Release of SDSS Quasar Catalog (Schneider et al. 2005) with the FIRST catalog (version 03Apr11, Becker et al.

1995) and NVSS catalog (Condon et al. 1998). Since we are interested in radio variable sources, which should contain a compact core on arcsec scales, we adopt a cutoff of two arcsecs in the position offset as the true match. As discussed in detail by several authors, this selection has chance coincidence of 0.1%, and is likely complete to 95% for point sources (e.g., Gregg et al. 1996). It will miss about 7% quasars with complex radio morphology or lobe dominated objects (Ivezić et al. 2002; Lu et al., in preparation). For NVSS sources, we adopt a cutoff of 15 arcsecs in the position offset between the SDSS quasar and the radio source. This will lead a completeness of 90%, while the false rate remains to be very low (4%). Since the NVSS covers the entire sky north of -40 declination, thus encompasses all sky covered by FIRST Survey. To ensure a high significance of detection in NVSS, we use a threshold of 5 mJy for the FIRST survey. Therefore, 2010 quasars with FIRST flux larger than 5 mJy were searched for their NVSS countparts. To complement with possible complex morphology, e.g., the bright lobes, the offset was increased up to 45", the beam size of the NVSS survey. All of the 2010 quasars have at least one NVSS countpart with 45".

Due to the different beam sizes used by NVSS and FIRST, one must be cautious while comparing their fluxes. We adopt a conservative approach in which only sources with the FIRST peak flux larger than the integrated flux of NVSS are considered as possible variable sources. Since the integrated NVSS flux may include diffuse emission or weak nearby radio sources, sources with NVSS flux larger than FIRST may well be due to such contaminations. In the next step, significance of the variation between the two epochs for each quasar is estimated as follows:

$$\sigma_{var} = \frac{S^{peak}_{FIRST} - S^{int}_{NVSS}}{\sqrt{\sigma^2_{FIRST} + \sigma^2_{NVSS} + (0.05 * S^{peak}_{FIRST})^2}} \tag{1}$$

where S^{peak}_{FIRST} is the peak flux during the FIRST survey, and S^{int}_{NVSS} the integrated NVSS flux, σ_{FIRST} and σ_{NVSS} the uncertainties in the correspondent FIRST and NVSS fluxes. The FIRST fluxes are subject to additional systematic uncertainties at 5% level, which is not included in the σ_{FIRST} (Becker et al. 1995). Note the 3% systematic uncertainty of NVSS flux has already been included in σ_{NVSS}. We use $\sigma_{var} > 3$ as a threshold for the source variability. Images of NVSS and FIRST are then visually examined for possible contamination due to nearby bright sources, and three of them were removed for this reason from the sample. SDSS J094420.44+613550.1 was eliminated from the sample because of NVSS catalog gives a wrong flux for this object. This gives a sample of 89 variable radio quasars with f_{FIRST}/f_{NVSS} in the range of 1.2 to 2.6. We expect that three out of them are spurious with this 3σ limits.

Radio loudness is calculated using the FIRST radio flux and the PSF magnitudes derived

from the SDSS survey as follows:

$$RL = (f_{1.4GHz}/f_{\nu,2500\mathring{A}}) \tag{2}$$

k-corrections to the optical flux is derived using the five SDSS magnitudes, corrected for the Galactic reddening. While we assume $\alpha_r = 0.0$ for the k correction of the radio flux of radio variable sources since they are likely flat spectral radio sources (see below). Apparently, 67% of radio variable sources are radio intermediate or radio quiet (Fig 1) according to the definition of Falcke et al. (1996a).

For the sources with significant flux variation, we compute the the lower limit of the brightness temperature by assuming the variable part of radio flux is emitted in a region of which the light-crossing time is equal to the separation of the two observations

$$T_B^l \sim \frac{\Delta P_\nu}{2k_B\nu^2\Delta t^2}, \tag{3}$$

where ΔP_ν is the variable part of the radio power computed from the difference between the FIRST and NVSS fluxes, Δt the timescale of the radio flux variability estimated from the difference of the observation time of FIRST and NVSS in the source rest frame, and k_B is the Boltzmann constant. Since $\nu\Delta t$ is Lorentz invariant, we simply use the observe frequency (1.4 GHz) and the separation of NVSS and FIRST observation dates. In cases where the FIRST observation date is only accurate to month, we use the day that makes the separation maximum to give a conservative estimate. The brightness temperatures inferred in this way are all larger than 10^{12} K except for two low redshift quasars (see also Table 1).

The upper limit of the brightness temperature from the synchrotron radiation of a stationary source due to inverse Compton process is approximately 10^{12} K (Kellermann & Pauliny-Toth 1969). This temperature may be greatly exceeded if the emission region moves relativistically towards the observer or if a coherent radiation process is responsible for the radio emission. In the former case, the apparent brightness temperature is boosted by a factor of

$$f = T_B^{var}/T_B^{intr} = D^3 \tag{4}$$

where $D = [\gamma * (1 - \beta\cos\theta)]^{-1}$ is the Doppler factor, $\gamma = 1/\sqrt{(1-\beta^2)}$, $\beta = v/c$, and θ is the angle between the line of sight and the velocity of the jet. However, it was shown that real radio sources may emit at equi-partition brightness temperature around 10^{11} K in most circumstance (e.g., Readhead 1994). In this paper, we adopt the inverse Compton limit as a secure upper limit to estimate the lower limit of the Doppler factor for the sources with brightness temperatures greater than this limit.

The lower limits of the Doppler factors we derived are in the range of 0.6-25 with a median around 4. For these radio variable sources, the maximum brightness attained ($\sim$

10^{16} K) are similar for radio loud, radio intermediate quasars (**?**). Note that the lack of sources with high RL and low brightness temperature T_B in the figure is due to a selection effect that sources with higher RL tend to be brighter in radio, thus have much higher radio power variation ΔP based on similar fractional variation amplitudes.

The fraction of variable sources varies with the radio power and radio loudness (**?**). The probability for a constant fraction at different radio power is only 2×10^{-5} ($D = 0.255$) using two sided Kolmogorov-Smornov test for two unbined distributions if an average radio spectral index $\alpha = 0.5$ for the parent sample of radio loud quasars. It increases to 2% if $\alpha = 0.0$ is used. Sources appears most-variable for radio powers in the range of $10^{24}-10^{26.5}$ W Hz^{-1} and least variable in $10^{26.5} - 10^{28}$ W Hz^{-1}. Quasars are more likely variable at radio loudness $< 10^{2.5}$ than above this value. The radio loudness distributions for variable and parent samples are drawn from the same population at a probability of only 10^{-7} (1%) using two-sided Kolmogorov-Smornov test for two unbinned distributions if α_r=0.0 (0.5) is used for k-correction in radio flux. Excluding radio sources with deconvolved major axis of the FIRST image larger than 3 arcsecs has little effect on these results.

The detection rate does not change with the separation of the two epoches, which is in the range of 0.4 to 5 years in the source rest frame (**?**). This is a possible indication that the variability is dominated by flares, similar to what observed in III Zw 2, but rather than long term smooth variations.

With the Doppler factor, we estimate the maximum viewing angle between the line of sight and the jet assuming an intrinsic narrow jet as follows,

$$\cos\theta_0 = \min([1 - \sqrt{(1-\beta^2)}/D]/\beta) \quad for\ all\ \beta \leq 1 \tag{5}$$

The inferred maximum viewing angles are quite small (usually, ≤15°) for most radio variable sources. And in some extreme objects, this angle is even smaller than the opening angle of jets on parsec scales or kpc scales in nearby radio galaxies (typical of 5°, e.g., Ly, Walker & Wrobel 2004).

Four quasars showed variations of a factor more than two between NVSS and FIRST surveys. Three of them are radio intermediate even at their peak radio flux during the FIRST survey. Their radio powers at 20cm are moderate ($24.9 < \log\ P_{20\mathrm{cm}} < 25.9$). The fastest variation among them is a factor of 2.5 in 20 cm flux within eight months for SDSS J073938.85+305951.2. We examined the optical spectra for possible evidence of blazar-like feature but fails to find any. In particular, the line and continuum spectra appear similar to the composite quasar spectra (VanDen Berk et al. 2001).

Some interesting objects are noted. This sample contains several radio loud BAL QSOs, which were analyzed in detail in Zhou et al. (2005). SDSS 094857.31+002225.5 is an ex-

tremely radio loud NLS1 with prominent optical FeII emission and inverted radio spectrum. It was studied in detail by Zhou et al. (2003). They proposed a relativisitic jet in this object based on the flux variability between the FIRST and NVSS data. It was observed by VLBA in 2 and 8.4GHz, and remains unresolved (Beasley et al. 2002), consistent with the conclusion reached by Zhou et al.. With an inferred Doppler factor of >4.3, the intrinsic radio loudness of this object is in the radio intermediate range if most of the radio flux is contributed by the beaming component.

For 10 radio variable objects that the non-simultaneous multi-wavelength radio observations are available, the radio spectral indices are in the range of $-0.2 \leq \alpha \leq 0.6$ ($f_\nu \propto \nu^\alpha$) with a median of 0.2. This is also consistent with boosted radio emission.

3. Discussion

Among 2010 quasars with FIRST flux larger than 5 mJy, we identified 89 radio variable ones. For strong sources, the systematic uncertainty limits any variation detectable to $\gtrsim$20% at 3σ levels (5% systematic uncertainty in the FIRST flux and 3% in the NVSS flux). At lower radio flux, the statistical fluctuation is significant, the limit increases to $\simeq$ 30% at flux limit of 5 mJy. Considering that we counted only sources with $f_{FIRST} > f_{NVSS}$, about 9% quasars with radio flux larger than 5 mJy show variations in 20 cm radio flux at 20-30% level on time scale of years.

We have found strong evidence for relativistic beaming in 87 of these 89 radio variable quasars. Among them, two are radio quiet ($RL < 10$) and 29 are radio loud ($RL > 250$), while the majority (56) are radio intermediate. Since radio powers of most (70%) these radio intermediate quasars are above the break power between FR I and FR II division ($\log P_{20cm}(W\ Hz^{-1}) \simeq 25.0$), one may question whether they are true radio intermediate quasars. However, radio powers of most these quasars are boosted by relativistic effect and as such represent only upper limits. The intrinsic radio power may be much lower. For example, if we use the lower limits of Doppler factor derived from the radio variability to de-boost the radio flux, the radio powers for these sources would be a factor of 10-1000 lower [1], well in the range for FR I galaxies. Of course this correction is oversimplified considering the contribution from lower velocity part of the jet and extended lobes, and the true powers may lie in between. By noting that the radio powers of most objects are not too far from the break power, even if substantial correction by the boosting effect is introduced, most of

[1]Radio flux from jet has been boosted by a factor of $D^{2+\alpha}$ for an optically thin jet model and $D^{3+\alpha}$ for isotropic emission model.

these quasars would be in the FR I regime. Therefore, we believe that most of objects with $RL < 250$ are radio intermediate as proposed by Fackle et al.. This is hitherto the largest sample of radio intermediate quasars with beamed radio emission.

Among 2010 radio quasars with 20 cm flux above 5 mJy, 724 objects show radio loudness $RL < 250$. Since radio spectral indexes are not available for all these sources, we can only set an upper limit on the number of radio intermediate quasars in the sample to 724. Among them we detected 58 quasars with relativistic jets beaming toward us. This leads to an apparent fraction to $\gtrsim$8.0%. However, a number of serious corrections must be applied in order to estimate the fraction of quasars with relativistic jets.

First, because of large inferred Doppler factor for these 58 radio intermediate/quiet quasars, they must be observed very close to the direction of jet. We estimate that the line of sight is within 15° of the jet direction for most variable objects (Eq. 2), thus the probability of detecting such a source is small. This implies that their parent population may be large. Second, since the quasars in the variable sample are relativistically boosted, the flux limit of the parent population may be well below 5 mJy, which is used to select the sample. Both effects depends on the Doppler factor: sources with a larger Doppler factor are seen at a small solid angle around the jet direction, and their fluxes are boosted by a larger factors. Using the maximum extending angles estimated in the last section, we estimate that the minimum size of parent quasar population at an opening angle less than θ (or with a given D) using:

$$N(> D) = \frac{\text{number of objects with} \cos\theta_0 \leq \cos\theta}{(1 - \cos\theta)}, \tag{6}$$

where $\cos\theta$ is the $\cos\theta_0$ for Doppler factor D $(Eq.\ 5)$. The result is plotted in **?**. The number of parent sources increases with the Doppler factor. This is in fact fully consistent with the assumption that the radio flux in these variable sources are boosted greatly by relativistic effect, as such objects with larger Doppler factor trace a larger parent population with a lower flux limit. At Doppler factor larger than 5, the radio variable sources traces a parent population $\approx$ 1500-2000. The number should be doubled since we consider only these sources with FIRST flux larger than the NVSS one. This number is a factor of 4 larger than all radio intermediate quasars at flux limit of 5 mJy even we relax the radio loudness of radio intermediate quasars to $RL < 250$ for all quasars.

The ratio of jet component at its comoving frame to the isotropic component is needed to determine the flux limit of parent population with a given Doppler factor, which is required to estimate the number of parent population. However, this is not constrained even for the best studied radio intermediate quasar, III Zw 2. In that case, the observed flux for extended lobe is 10-20% of the core component, and apparent velocity is 2.6c. Since we do not know the angle between the line sight to the jet, it Doppler factor cannot be determined.

Fortunately, a meanful conclusion can still be reached with the current data. If the radio emission of quasars with $D \simeq 5$ have been boosted by a factor of 10, then the flux limit of parent population is 0.5 mJy for our sample. Note that to the FIRST flux limit (1 mJy), 4124 (5313) among 44984 quasars in SDSS DR3 are detected in the FIRST with 3 arcsec offset in the flux limit of $\sim$ 1 mJy ($\sim$0.7 mJy) (de Vries, Becker & White 2005). Most of them are radio intermediate (see Iveciz et al. 2003). Extrapolating to 0.5mJy will predict the number of radio detectable quasars to 6751. With this assumption, the parent population of the radio variable sources would be as large as half of quasars with radio flux larger than 0.5 mJy. Alternatively, if the isotropic component (lobes) is very weak for these radio intermediate quasars, then the flux limit of the parent population is even lower, we will detect a small fraction of relativistic jets but intrinsically radio even weak quasars.

Note this number is likely a conservative lower limit because not all quasars with relativistic jets shows radio variations at amplitude greater than our detection limits during the epoch of two radio observations. Thus we believe that relativistic jets present in most radio intermediate quasars.

Our results imply that jets in a large fraction of radio intermediate sources are relativistic, but the size of emission region is smaller than in classical radio loud quasars. A substantial fraction of 20 cm radio flux is emitted on the scales of several to tens parsecs as suggested by the variability time scale. The peak brightness or the Lorentz factor of the most compact component is similar for both radio loud and radio intermediate quasars. The typical size of radio loud objects, however, appears larger given their large radio powers. As a result, the 20 cm radio emission in the classical radio sources is less variable on time scales of years. This is consistent with our results that the fraction of radio variable source is small at very large radio loudness.

The presence of relativistic jets on parsec scales in a substantial fraction of radio intermediate quasars has several implications for AGN models. If the radio emission has been boosted by relativistic effect and the emission from extended lobes are weak as of III Zw 2, many flat spectral intermediate radio quasars might be boosted radio-quiet quasars. If the broad band spectrum of jet component is similar to that of low peak BL Lacs while the disk emission component is similar to that of other quasars, we estimate that the jet emission will dominate the SED at sub-mm wavelength, and contribute significantly to the hard X-ray spectrum of those beamed objects.

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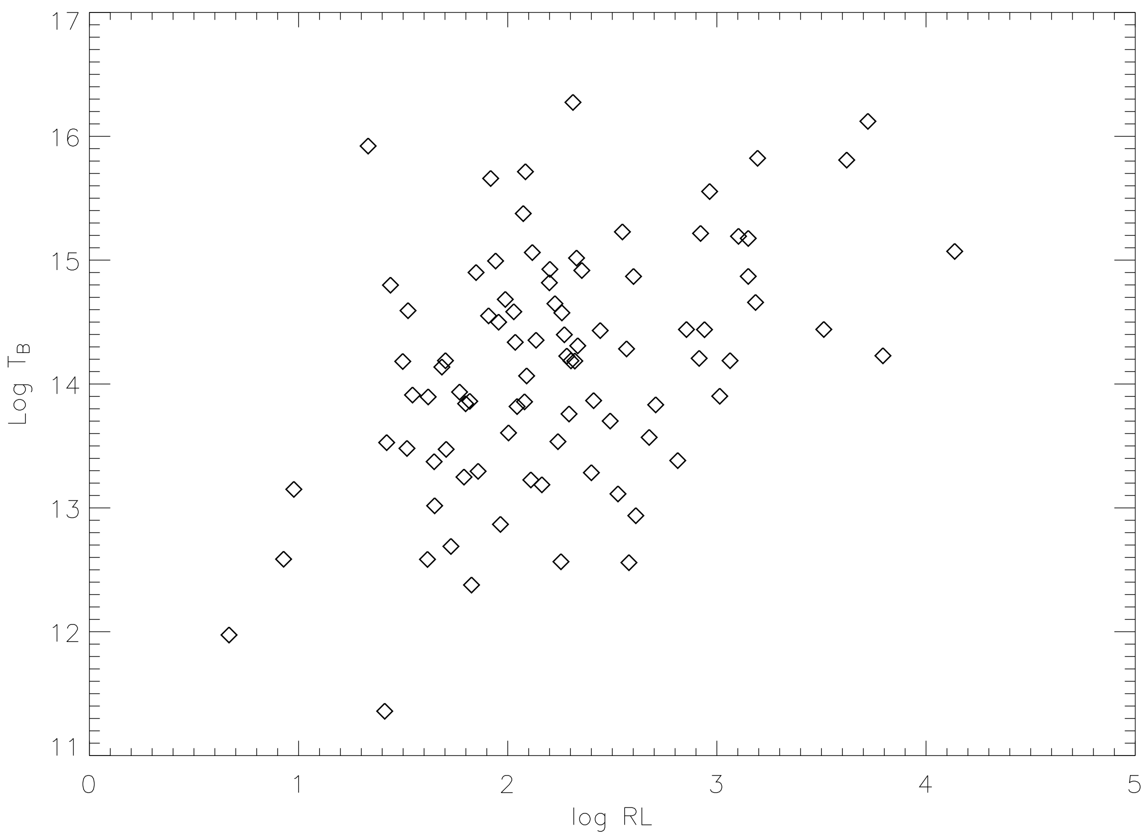

Fig. 1.— The brightness temperature versus radio loudness for 89 radio variable quasars.

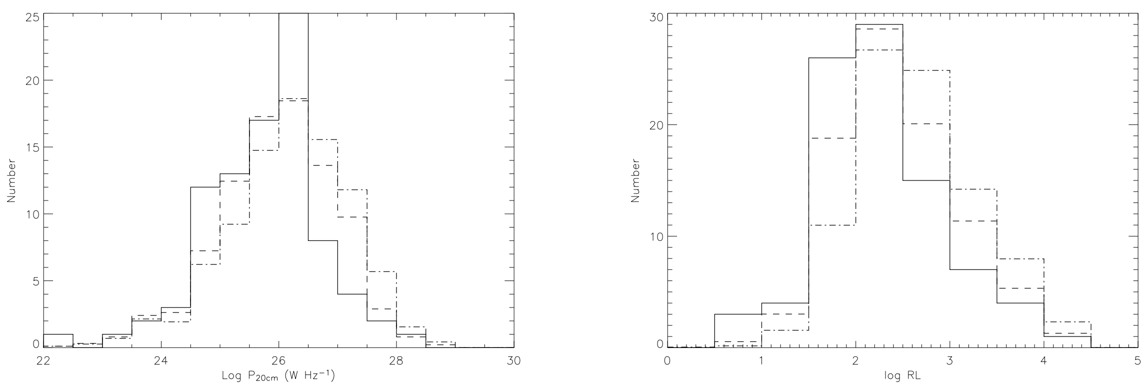

Fig. 2.— The distribution of radio loudness (left panel) and radio power (right panel) for radio variable quasar sample (solid line) and the parent radio selected quasar sample (dashed line: k-correction with $\alpha_r = 0$, dash-dot line: $\alpha_r = 0.5$). The number of quasars in the parent sample is normalized to the former.

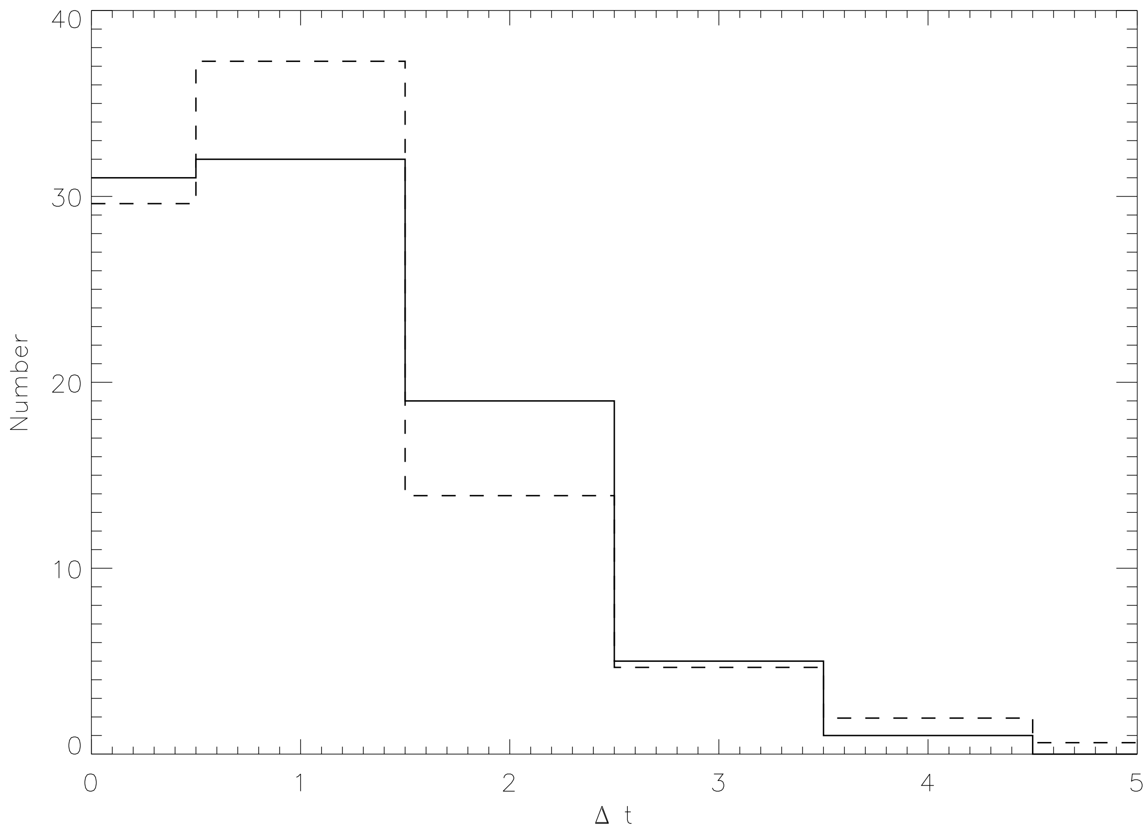

Fig. 3.— The distribution of the separation between FIRST and NVSS observations for the variable sample and the parent sample.

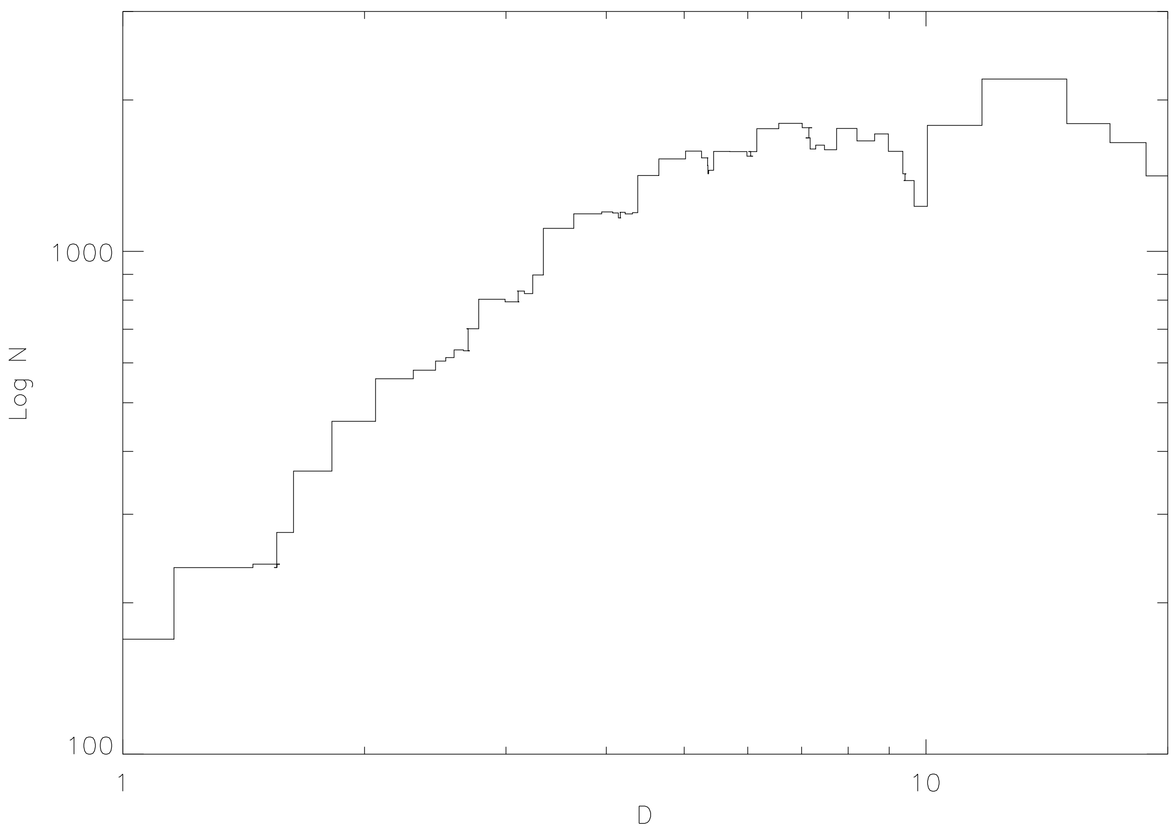

Fig. 4.— The expected number of parent population versus Doppler factor (See Eq. 6).

Table 1. Basic data of Radio Variable Quasars

Coordinates (J2000) hhmmss.ss±ddmmss.s	Redshift	g' mag	S^{p}_{FIRST} mJy	FIRST Date yyyy-mm-dd	S^{int}_{NVSS} mJy	NVSS Date yyyy-mm-dd	$\log RL$	$\log T_B$ K	D
010249.65−085344.4	1.6825	18.484±0.014	8.35± 0.15	1997-02-	5.70± 0.50	1993-09-20	1.54	13.91	4.34
013146.43−084104.1	1.6512	19.488±0.023	5.47± 0.15	1997-02-	3.00± 0.50	1993-09-20	1.82	13.86	4.17
015153.30−002850.2	1.9950	18.076±0.016	12.14± 0.15	1995-11-14	9.20± 0.50	1993-11-15	1.52	14.59	7.31
073938.85+305951.2	3.3994	21.256±0.040	7.26± 0.37	1993-04-12	2.80± 0.40	1993-12-15	2.31	16.27	26.58
074033.54+285247.1	0.7111	19.376±0.020	77.57± 0.15	1993-04-29	63.30± 1.90	1993-12-15	3.15	15.18	11.44
074815.44+220059.5	1.0595	16.437±0.015	9.86± 0.13	1998-08-	7.00± 0.40	1993-11-01	0.98	13.15	2.42
074823.85+332051.2	2.9888	20.036±0.021	8.14± 0.14	1995-10-	5.90± 0.40	1993-12-15	1.94	14.99	9.95
075535.41+292047.3	0.5064	18.552±0.115	7.19± 0.15	1993-05-04	5.40± 0.40	1993-12-15	1.77	13.94	4.42
075849.47+305452.8	2.7967	19.720±0.020	5.92± 0.14	1993-04-13	4.20± 0.40	1993-12-15	1.92	15.66	16.60
080945.16+453918.0	2.0395	20.708±0.030	20.59± 0.13	1997-03-18	15.10± 0.60	1993-11-15	2.85	14.44	6.51
081352.87+352035.4	1.8981	19.622±0.019	8.01± 0.13	1994-07-03	4.70± 0.40	1993-12-15	2.08	15.71	17.30
081415.05+412323.4	1.2969	18.487±0.025	5.15± 0.13	1994-09-02	3.40± 0.40	1993-12-15	1.44	14.80	8.57
081655.28+475611.5	2.2337	20.293±0.025	9.01± 0.47	1997-04-05	4.90± 0.40	1993-11-15	2.27	14.40	6.30
082817.25+371853.7	1.3530	21.675±0.056	21.18± 0.13	1994-07-23	14.80± 0.60	1993-12-15	2.97	15.55	15.30
083225.34+370736.2	0.0919	16.173±0.014	11.78± 0.17	1994-07-23	8.20± 0.50	1993-12-15	0.93	12.59	1.57
083655.73+342335.4	0.7905	20.258±0.025	10.32± 0.13	1994-07-01	6.30± 0.40	1993-12-15	2.60	14.87	9.04
083658.91+442602.3	0.2544	15.613±0.027	9.39± 0.15	1997-02-28	6.60± 0.50	1993-11-15	0.67	11.97	0.98
083744.01+420643.9	2.1301	19.337±0.024	18.12± 0.13	1995-12-19	13.50± 0.60	1993-11-15	2.20	14.82	8.69
083951.00+333630.9	1.7528	19.953±0.023	5.60± 0.14	1994-06-19	4.00± 0.40	1993-12-15	2.07	15.38	13.35
084955.28+005305.5	1.0345	18.639±0.021	6.20± 0.15	1998-08	4.00± 0.40	1993-11-15	1.65	13.02	2.18
084957.97+510829.0	0.5837	18.956±0.021	344.09± 0.14	1997-04-25	266.30± 8.00	1993-11-15	3.79	14.23	5.53
085001.17+462600.5	0.5238	19.137±0.022	20.90± 0.13	1997-03-22	16.00± 0.60	1993-11-15	2.61	12.94	2.05
085217.84+054027.8	0.8520	20.915±0.035	5.45± 0.15	2000-02-	3.30± 0.40	1993-11-15	2.58	12.56	1.54
085958.69+455237.9	0.4400	18.860±0.020	30.74± 0.14	1997-03-22	19.60± 0.70	1993-11-15	2.53	13.11	2.35
090111.86+044858.8	1.8626	19.526±0.023	133.57± 0.15	2000-02-	94.30± 2.90	1993-11-15	3.18	14.66	7.70
090155.15+425404.4	1.7350	19.518±0.021	14.23± 0.14	1997-02-17	9.90± 0.50	1993-11-15	2.32	14.19	5.35
090412.87+060326.5	0.9360	18.171±0.024	8.01± 0.15	2000-02-	6.20± 0.40	1993-11-15	1.62	12.58	1.57
090743.66+551512.4	0.6448	17.409±0.014	22.58± 0.14	1997-03-	16.80± 0.60	1993-11-23	1.79	13.25	2.61
091641.76+024252.8	1.1025	19.121±0.016	99.39± 0.14	1998-07-	72.50± 2.20	1993-11-15	3.06	14.19	5.36
093215.14+432738.4	0.9564	18.237±0.052	20.43± 0.13	1997-02-20	12.30± 0.50	1993-11-15	2.04	13.82	4.04
093323.02−001051.6	0.7949	18.613±0.014	101.36± 0.15	1998-08-	66.80± 2.00	1995-02-27	2.92	14.21	5.44
093818.35+390809.8	1.3049	20.423±0.028	7.43± 0.13	1994-08-13	5.50± 0.50	1993-12-15	2.35	14.92	9.38
094857.31+002225.5	0.5846	18.661±0.012	107.53± 0.15	1998-09-	69.50± 2.10	1995-02-27	3.01	13.90	4.30
095046.47+584113.0	2.3648	20.426±0.025	6.54± 0.14	2002-06-	4.80± 0.40	1993-11-23	2.40	13.28	2.68
095147.86+020235.5	0.6053	18.424±0.024	6.14± 0.15	1998-07-	4.20± 0.50	1995-02-27	1.73	12.69	1.70
095227.30+504850.6	1.0909	17.848±0.032	104.85± 0.15	1997-04-25	85.80± 3.00	1993-11-15	2.57	14.28	5.77
095618.17+542628.2	1.7147	19.169±0.021	8.72± 0.14	1997-05-	6.40± 0.50	1993-11-23	2.08	13.86	4.16
095739.92+074047.9	1.6688	19.454±0.023	73.56± 0.15	2000-01-	54.70± 1.70	1995-02-27	2.94	14.44	6.50
095819.66+472507.8	1.8818	18.545±0.025	763.01± 0.15	1997-03-31	603.80±18.10	1993-11-15	3.62	15.81	18.59
101609.48+002810.5	1.0131	19.891±0.022	22.47± 0.15	1998-08-	18.10± 0.70	1995-02-27	2.68	13.57	3.34
103424.41+493221.0	1.6163	20.105±0.020	12.42± 0.13	1997-04-17	9.70± 0.50	1993-11-15	2.41	13.87	4.19
104901.71+005534.0	1.1633	18.408±0.031	5.73± 0.15	1998-08-	3.20± 0.40	1995-02-27	1.52	13.48	3.12
105320.42−001649.6	4.3032	21.952±0.085	13.31± 0.15	1998-08-	9.30± 0.50	1995-02-27	2.12	15.06	10.49
110845.28+594137.9	0.7476	18.457±0.026	8.95± 0.14	2002-07-	5.20± 0.40	1993-11-23	1.83	12.38	1.34
110859.29+031127.9	3.4587	20.136±0.036	10.36± 0.15	1998-09-	7.40± 0.50	1995-02-27	1.99	14.68	7.84

Table 1—Continued

Coordinates (J2000) hhmmss.ss±ddmmss.s	Redshift	g' mag	S^{p}_{FIRST} mJy	FIRST Date yyyy-mm-dd	S^{int}_{NVSS} mJy	NVSS Date yyyy-mm-dd	$\log RL$	$\log T_B$ K	D
111030.44+034833.3	1.8653	19.435±0.021	15.37± 0.13	1998-07-	11.20± 0.50	1995-02-27	2.28	14.23	5.52
111221.82+003028.5	0.5234	19.417±0.029	8.88± 0.14	1998-08-	6.70± 0.50	1995-02-27	2.25	12.57	1.54
114856.79+555827.3	0.9616	19.267±0.074	21.88± 0.14	1997-05-	15.10± 0.90	1993-11-23	2.49	13.70	3.69
120331.10−014111.6	1.8316	18.308±0.015	11.84± 0.14	1998-08-	8.10± 0.50	1995-02-27	1.69	14.14	5.16
121143.52+013011.2	2.5902	18.520±0.041	18.36± 0.15	1998-07-	14.40± 0.60	1995-02-27	1.91	14.55	7.08
121440.07+600330.9	1.4863	18.589±0.026	34.02± 0.14	2002-07-	17.50± 0.70	1993-11-23	2.29	13.76	3.86
121446.06+532023.5	2.1472	19.686±0.024	13.02± 0.22	1997-05-05	8.90± 0.90	1993-11-15	2.04	14.34	6.01
121729.29+060750.8	2.0945	19.587±0.019	24.49± 0.17	2000-02-	13.50± 0.60	1995-02-27	2.44	14.43	6.46
121729.84−004715.7	1.3371	20.205±0.049	18.83± 0.14	1998-08-	14.80± 0.60	1995-02-27	2.71	13.83	4.08
121916.76+623026.1	3.0559	19.553±0.025	8.40± 0.14	2002-07-	6.40± 0.40	1993-11-23	2.00	13.61	3.43
122400.78+005919.9	1.4956	19.475±0.020	5.52± 0.14	1998-08-	2.40± 0.50	1995-02-27	1.80	13.84	4.11
122705.72+631533.2	1.5937	19.672±0.031	5.02± 0.13	2002-08-	3.20± 0.40	1993-11-23	1.97	12.87	1.95
122757.23+101410.7	1.2924	18.145±0.032	7.24±0.14	200001	2.90±0.60	1995-02-07	1.40	13.53	4.33
122819.25+023229.3	3.1479	20.638±0.032	111.11± 1.72	1998-09-	60.00± 1.80	1995-02-27	3.19	15.82	18.80
122956.17−012910.6	0.9991	19.673±0.021	6.55± 0.15	1998-08-	4.50± 0.40	1995-02-27	2.11	13.23	2.56
123132.37+013814.0	3.2286	19.205±0.026	11.51± 0.81	1998-07-	6.30± 0.40	1995-02-27	1.85	14.90	9.26
123628.79+565156.4	2.5105	20.260±0.025	8.36± 0.14	1997-05-	6.40± 0.40	1993-11-23	2.30	14.19	5.36
123932.75+044305.3	1.7621	20.481±0.025	426.95± 0.14	2000-02-	353.80±10.60	1995-02-27	4.14	15.07	10.56
125014.30+621032.4	1.9053	19.615±0.020	11.54± 0.15	2002-07-26	9.10± 0.50	1993-11-23	2.16	13.19	2.49
125414.27+024117.5	1.8405	18.816±0.020	6.42± 0.14	1998-07-	4.40± 0.40	1995-02-27	1.62	13.90	4.29
131728.65+060046.5	2.6095	19.127±0.020	76.59± 0.14	2000-02-	37.40± 1.20	1995-02-27	2.92	15.22	11.80
131906.47+493152.9	1.9322	18.887±0.019	13.65± 0.13	1997-04-17	10.20± 0.50	1995-03-12	2.03	14.58	7.27
135213.31+581536.8	3.1136	19.024±0.028	13.54± 0.13	2001-03-	9.60± 0.50	1993-11-23	2.09	14.07	4.88
135341.72+431052.5	1.1136	17.274±0.023	23.15± 0.14	1997-02-20	18.50± 0.70	1995-03-12	1.70	14.19	5.37
142730.43+545601.6	1.7533	17.763±0.024	32.85± 0.15	1997-03-	24.10± 0.80	1993-11-23	1.96	14.50	6.81
143540.20+024226.4	2.1812	19.945±0.023	57.82± 0.14	1998-07-	45.30± 1.40	1995-02-27	3.15	14.87	9.04
143623.97+031155.5	1.7979	19.319±0.022	16.63± 0.33	1998-07-	10.50± 0.50	1995-02-27	2.14	14.35	6.09
145002.45+001629.4	0.9573	19.145±0.015	13.82± 0.17	1998-07-	9.40± 0.50	1995-02-27	2.24	13.54	3.25
145207.94+025019.4	2.4330	20.262±0.031	11.17± 0.13	1998-07-	6.30± 0.50	1995-02-27	2.26	14.57	7.21
150205.38+604534.3	1.2986	19.690±0.021	44.89± 0.15	2002-07-	35.20± 1.10	1993-11-23	2.81	13.38	2.89
151002.93+570243.3	4.3087	22.055±0.065	248.07± 0.13	1997-05-	202.00± 6.10	1993-11-23	3.72	16.12	23.64
153559.67+583430.9	2.1813	18.620±0.025	6.70± 0.13	2002-06-	4.10± 0.40	1993-11-23	1.65	13.37	2.87
153703.94+533219.9	2.4035	18.133±0.024	9.28± 0.14	1997-05-	7.10± 0.40	1993-11-15	1.50	14.18	5.34
162548.79+264658.7	2.5177	17.340±0.017	10.12± 0.13	1995-12-17	6.10± 0.40	1995-04-16	1.33	15.92	20.29
162816.95+351023.6	0.7151	18.713±0.019	15.91± 0.14	1994-07-03	9.40± 0.50	1995-04-16	2.23	14.65	7.64
163915.80+412833.7	0.6900	19.133±0.016	89.23± 0.16	1994-09-02	73.80± 2.30	1995-04-16	3.10	15.19	11.60
164602.25+432156.3	2.9102	20.603±0.025	6.21± 0.14	1997-02-20	3.80± 0.40	1995-03-12	2.20	14.93	9.45
164952.90+325815.1	0.7109	18.530±0.013	43.58± 0.12	1995-10-14	33.60± 1.10	1995-04-16	2.55	15.23	11.91
171535.96+632336.0	2.1818	18.584±0.019	52.48± 0.14	2002-08-	35.90± 1.10	1995-04-02	2.33	14.31	5.88
210757.67−062010.6	0.6456	17.496±0.014	19.21± 0.14	1997-02-	12.40± 0.60	1993-09-20	1.86	13.30	2.70
230845.85+011201.3	3.0559	20.146±0.025	8.06± 0.13	1995-10-16	5.50± 0.40	1993-11-15	2.33	15.02	10.13